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Analysis and Prediction of Size Effect on Laser Forming of Sheet Metal

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Abstract

Geometric effects play an important role in laser forming processes; however, few investigations have explored geometric effects other than those induced by sheet thickness. In this paper, the influence of component size or size effect, including variation of sheet width and sheet length, on laser-induced deformation is experimentally, numerically, and analytically investigated. An experimental matrix is designed to cover a wide range of sheet width and length for experiments and numerical simulation under different process conditions. Distinctive trends in bending angle are identified for varying sheet width, length, or both. The results are interpreted in terms of heat sink effect and bending nonuniformity. An analytic model is developed to facilitate size effect prediction. The model is based on the solution to a moving strip heat source over a finite size sheet. It also accounts for the pre-bending effect among consecutive segments on the scanning path. Analytical results are compared with an existing analytical model and numerical simulation.

Keywords: *Size Effect, Laser Forming, Analytical Model, Sheet Metal*

Introduction

Laser forming is a flexible manufacturing process that forms sheet metal by means of stresses induced by external heat instead of external force. It is a nonlinear, thermomechanical process. Understanding various aspects of laser forming has been a challenging problem of considerable theoretical and practical interest. The relationships between bending distortion and process parameters, material properties, and workpiece thickness have been developed in analytical models. Additional information, such as influence of strain hardening, strain rate effects, and edge effect, has also been reported in experimental and numerical investigations.

The geometric effects in laser forming, however, have not been fully studied. Most research has focused on the effect of workpiece thickness without considering other geometric attributes of the workpiece. Scully (1987) proposed that plate thickness, s_0, is one of the primary factors in laser forming (two other primary factors are laser power, P, and scanning speed, V). Scully adopted a quantity, $P/\left(s_0\sqrt{V}\right)$, that was used in arc welding to study the effect of plate thickness on bending angle, but he did not give an exact relationship between them. Koloman and Karol (1991) proposed an analytical model to express the relationship between bending angle and sheet thickness based on a pure energy approach. In this model, the bending angle is a function of the reciprocal of the square of thickness. However, the bending angles calculated from this formula are some orders of magnitude too large compared with experiments. Vollertsen proposed a simple, two-layer model based on the temperature gradient mechanism (TGM), with the temperature field obtained by an energy approach (Vollertsen 1994a) or by solving the 3-D heat conduction problem (Vollertsen 1994b). Both of Vollertsen's models have the same assumption that bending deformation is uniform along the sheet length so that the only geometric factor appearing in those models is plate thickness. Although more analytical models (Yau, Chan, and Lee 1997; Cheng and Lin 2001) were proposed recently and better agreements with the experimental results were reported, none of them have considered the effect of sheet size on laser forming deformation.

Experimental investigations and numerical simulation, however, have shown that sheet size has an effect on laser forming. Vollertsen (1994a) pointed out that the width of the sheet influences the cooling conditions and, therefore, the bending angle, and he also observed the influence of the sheet length on stress state. But he did not consider the size influences in his analytical solutions. Hsiao et al. (1997) found that for Inconel 625 the angular distortion

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increases as sheet length increases, and he proposed that the reason is that the longer plate provides more cold metal to produce thermal stresses. He also proposed that there is an upper limit in the angular distortion with respect to the sheet length. However, these investigations on the influence of component size or size effect were empirical and did not lead to analytical prediction.

In this paper, the size effect exhibited in the laser forming process is investigated. First, the experimental and numerical investigations aimed at advancing the understanding of the causes of the size effect in straight-line laser forming are presented for a wide range of sheet sizes. Various deformation patterns due to the size effect are explained. To better quantify the role of size effect on laser forming, a predictive model is developed, in which finite sheet width and length are considered. The proposed model is experimentally validated.

Experiments and Simulation

Experiments of straight-line laser forming (*Figure 1*) were carried out following the matrix shown in *Table 1*, where the first number represents sheet length, L, and the second represents sheet width, W. In the present paper, the sheet length is defined as the dimension in the scanning direction and the sheet width is defined as the dimension perpendicular to the scanning direction. In this way, the size effect was investigated in three cases: varying sheet width, varying sheet length, and varying square size. Besides the listed sizes, additional sets of samples (L = 20~60 mm, W = 80 mm) were used to further investigate the sheet length effect because it was reported (Vollertsen 1994a,b) that the effect of sheet length is more pronounced when the length-to-thickness ratio (L / s_0) is small. The sheet thickness is fixed at 0.89 mm because the effect of thickness has been well studied and documented, as discussed in the previous section. Two sets of the experiments, with laser power 800 W, scanning velocity 50 mm/s and laser power 400 W, scanning velocity 25mm/s, were carried out. Although they involve the same line energy (P/V), the size effect on deformation may not be the same. The material investigated is cold-rolled AISI 1010 steel. The laser system used in the experiments is a PRC-1500 CO_2 laser, with a maximum output power of 1.5 kW and power density distribution of TEM_{00}. The diameter of the laser beam used is 4 mm, which is defined as the diameter at which the power density becomes $1 / e^2$ of the maximum power value. A coordinate measuring machine (CMM) is used to measure the bending angle. Bending angle may vary slightly along the scanning path, which is known as the edge effect (Bao and Yao 2001). Hence, bending angle was measured at five equally spaced locations along the scanning path and an average was calculated. To enhance laser absorption by the workpiece, graphite coating was applied to the surface exposed to the laser.

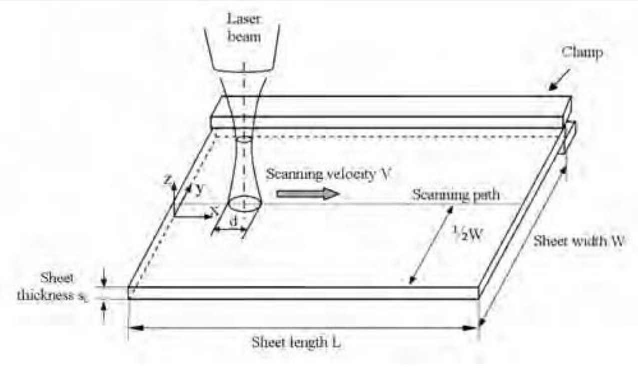

Figure 1
Schematic of Straight-Line Laser Bending

In numerical simulation, the laser forming process is modeled as a sequentially coupled thermal-mechanical process. In the thermal analysis, all the surfaces of the workpiece are subject to the convective heat flux, that is, $f = h(T - T_s)$, where h is the convective heat transfer coefficient, T is the surface temperature, and T_s is the surrounding temperature. The radiation heat flux is also considered at the heating surface, which is $f_c = \varepsilon\sigma(T^4 - T_s^4)$, where ε and σ are emissivity and the Stefan-Boltzmann constant, respectively. More details can be found in Cheng and Yao (2003).

In the mechanical analysis, direct integration of the system is used for the nonlinear transient dynam-

Table 1
Experiment Conditions for Size Effect
(unit: mm; sheet size: Length × Width (*L* × *W*)
below and throughout the paper)

Length \ Width	80	120	160	200
80	80×80	80×120	80×160	80×200
120	120×80	120×120		
160	160×80		160×160	
200	200×80			200×200